Can TMT Image Habitable Planets?

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Why directly imaging?

Spectra can also be obtained by transit, but:
- Low probability (few %)
- High atmosphere only

Spectra of Earth (taken by looking at Earthshine) shows evidence for life and plants

Woolf et al.
Taking images of exoplanets: Why is it hard?
Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired [assumes 1e-8 contrast limit, 1 λ/D IWA]

K-type and nearest G-type stars are more challenging, but could be accessible if raw contrast can be pushed to ~1e-7 (models tell us it's possible)

Thermal emission from habitable planets around nearby A, F, G type stars is detectable with ELTs
Contrast and Angular separation (updated)

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Thermal emission from habitable planets around nearby A, F, G type stars is detectable with ELTs

1 Re rocky planets in HZ for stars within 30pc (6041 stars)
What is so special about M stars?

They are **abundant**: >75% of main sequence stars are M type

<table>
<thead>
<tr>
<th>Class</th>
<th>Effective temperature</th>
<th>Vega-relative &quot;color label&quot;</th>
<th>Chromacity</th>
<th>Main-sequence mass</th>
<th>Main-sequence radius</th>
<th>Main-sequence luminosity</th>
<th>Hydrogen lines</th>
<th>Fraction of all main-sequence stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>≥ 30,000 K</td>
<td>blue</td>
<td>blue</td>
<td>≥ 16 $M_\odot$</td>
<td>≥ 6.6 $R_\odot$</td>
<td>≥ 30,000 $L_\odot$</td>
<td>Weak</td>
<td>-0.00003%</td>
</tr>
<tr>
<td>B</td>
<td>10,000–30,000 K</td>
<td>blue white</td>
<td>deep blue white</td>
<td>2.1–16 $M_\odot$</td>
<td>1.8–6.6 $R_\odot$</td>
<td>25–30,000 $L_\odot$</td>
<td>Medium</td>
<td>0.13%</td>
</tr>
<tr>
<td>A</td>
<td>7,500–10,000 K</td>
<td>white</td>
<td>blue white</td>
<td>1.4–2.1 $M_\odot$</td>
<td>1.4–1.8 $R_\odot$</td>
<td>5–25 $L_\odot$</td>
<td>Strong</td>
<td>0.6%</td>
</tr>
<tr>
<td>F</td>
<td>6,000–7,500 K</td>
<td>yellow white</td>
<td>white</td>
<td>1.04–1.4 $M_\odot$</td>
<td>1.15–1.4 $R_\odot$</td>
<td>1.5–5 $L_\odot$</td>
<td>Medium</td>
<td>3%</td>
</tr>
<tr>
<td>G</td>
<td>5,200–6,000 K</td>
<td>yellow</td>
<td>yellowish white</td>
<td>0.8–1.04 $M_\odot$</td>
<td>0.96–1.15 $R_\odot$</td>
<td>0.6–1.5 $L_\odot$</td>
<td>Weak</td>
<td>7.6%</td>
</tr>
<tr>
<td>K</td>
<td>3,700–5,200 K</td>
<td>orange</td>
<td>pale yellow orange</td>
<td>0.45–0.8 $M_\odot$</td>
<td>0.7–0.96 $R_\odot$</td>
<td>0.08–0.6 $L_\odot$</td>
<td>Very weak</td>
<td>12.1%</td>
</tr>
<tr>
<td>M</td>
<td>2,400–3,700 K</td>
<td>red</td>
<td>light orange red</td>
<td>0.08–0.45 $M_\odot$</td>
<td>≤ 0.7 $R_\odot$</td>
<td>≤ 0.08 $L_\odot$</td>
<td>Very weak</td>
<td>76.45%</td>
</tr>
</tbody>
</table>

Within 5pc (15ly): 60 hydrogen-burning stars, 50 are M type, 6 are K-type, 4 are A, F or G

4.36  Alpha Cen A  
8.58  Sirius A  
11.40  Procyon A  
11.89  Tau Ceti

4.36  Alpha Cen B  
10.52  Eps Eri  
11.40  61 Cyg A  
11.40  61 Cyg B  
11.82  Eps Ind A  
15.82  Gliese 380
What is so special about M stars?

Strong evidence that their systems are rich in terrestrial planets:

- Planet formation models evidence
- Lack of giant planets near HZ → good thing!
- Kepler data shows trend: more rocky planets around M-type stars
- Recent discoveries:
  Prox Cen b
  Trappist-1
Habitable Zones within 5 pc (16 ly):
Astrometry and RV Signal Amplitudes for Earth Analogs

Star Temperature [K]

Circle diameter is proportional to 1/distance
Circle color indicates stellar temperature (see scale right of figure)

Astrometry and RV amplitudes are given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)

Expected detection limit for space astrometry (NEAT, THEIA, STEP) F, G, K stars

Expected detection limit for near-IR RV surveys (SPIROU, IRD + others) M-type stars
Habitable Zones within 5 pc (16 ly)

Circle diameter indicates angular size of habitable zone
Circle color indicates stellar temperature (see scale right of figure)
Contrast is given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)
Habitable Zones within 5 pc (16 ly)

- Inner Working Angle
- Flux (WFS and science)
- Contrast floor

Circle diameter indicates angular size of habitable zone
Circle color indicates stellar temperature (see scale right of figure)
Contrast is given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)
Coronagraphy ... Using optics tricks to remove starlight (without removing planet light)

← Olivier's thumb...
the easiest coronagraph
Doesn't work well enough to see planets around other stars

We need a better coronagraph... and a larger eye (telescope)
Water waves diffract around obstacles, edges, and so does light

Waves diffracted by coastline and islands

Ideal image of a distant star by a telescope
Diffraction rings around the image core
PIAACMC focal plane mask manufacturing

Focal plane mask manufactured at JPL's MDL
Meets performance requirements
(WFIRST PIAACMC Milestone report)

← SCExAO focal plane mask (Mar 2017)
PIAACMC lab performance @ WFIRST
(Kern et al. 2016)

Operates at 1e-7 contrast, 1.3 I/D IWA, 70% throughput
Visible light

non-coronagraphic PSF
Remapped pupil
Coronagraphic image
TMT coronagraph design for 1 I/D IWA

Pupil Plane

PIAACMC lens 1 front surface (CaF2)

PIAACMC lens 2 front surface (CaF2)

PSF at 1600nm
3e-9 contrast in 1.2 to 8 I/D
80% off-axis throughput
1.2 I/D IWA
CaF2 lenses
SiO2 mask

To be updated with new pupil shape
The REAL challenge: Wavefront error (speckles)

H-band fast frame imaging (1.6 kHz)
PREVIOUS technologies

30m: SH-based system, 15cm subapertures

Limited by residual OPD errors: time lag + WFS noise
kHz loop (no benefit from running faster) – same speed as 8m telescope
>10kph per WFS required

Detection limit ~1e-3 at IWA, POOR AVERAGING due to crossing time

Need 3 orders of magnitude improvement in contrast to reach habitable planets

Expected limit
Wavefront Control: Key challenges

[1] WFS efficiency
M stars are not very bright for ExAO → need high efficiency WFS
For low-order modes (TT), seeing-limited (SHWFS) requires \((D/r_0)^2\) times more light than diffraction-limited WFS
This is a \(40,000\) \textbf{gain for 30m telescope} (assuming \(r_0=15\)cm) → 11.5 mag gain

[2] Low latency WFC
System lag is extremely problematic → creates “ghost” slow speckles that last crossing time
Need \(\sim200\)us latency (10 kHz system, or slower system + lag compensation), or multiple loops

[3] WF chromaticity
Wavefront chromaticity is a serious concern when working at \(\sim1\)e-8 contrast
Visible light (\(\sim0.6 – 0.8\) um) photon carry most of the WF information, but science is in near-IR

[4] Non-common path errors
It doesn't take much to create a 1e-8 speckle!

[5] PSF calibration
What is a speckle, what is a planet?
Wavefront Control: ... and solutions

[1] Diffraction-limited pupil-plane WFS
Low or no modulation PyWFS is diffraction-limited
This is a 40,000x gain for 30m telescope (assuming r0=15cm) → 11.5 mag gain

Fast hardware (Cameras, GPUs) can now run loop at ~5 kHz on ELT
Example: SCExAO runs 2000 actuators, 14,400 sensors at 3.5kHz using ~10% of available RTS computing power

[1][2] Predictive Control
Eliminates time lag, improves sensitivity

[1][2][3][4][5] Fast speckle control, enabled by new detector technologies
Addresses simultaneously non-common path errors, (most of) lag error, chromaticity, and calibration

[5] Real-time telemetry → PSF calibration
WFS telemetry tells us where speckles are → significant gain using telemetry into post-processing

[5] Spectral discrimination
Especially powerful at high spectral resolution
Nominal ELT ExAO system architecture

**INSTRUMENTATION**

- **Thermal IR Imaging & spectroscopy**
- **Visible light Imaging, spectroscopy, polarimetry, coronagraphy**
- **Near-IR Imaging, spectroscopy, polarimetry**

- **Woofer DM**, ~2 kHz speed, 120 x 120 actuators, delivers visible diffraction-limited PSF to visible WFS
- **Tweeter DM**, 10 kHz response, 50 x 50 actuators, provides high contrast
- **Low-IWA coronagraph High efficiency**: Speed ~kHz, photon-counting detector
- **Speckle control afterburner WFS**: Speed ~kHz, photon-counting detector

- **Coronagraphic Low-order WFS uses light rejected by coronagraph**
  → catches aberrations BEFORE they hurt contrast
  → stellar leakage derived from telemetry

- **Visible / nearIR light low-latency WFS**
- **Diffraction limited sensitivity**

> focus

TT, focus?
High Speed Speckle Control

Main SCExAO upgrade: High speed speckle control with MKIDs

- Uncalibrated image
- Sum
- Unknown planet light (incoherent)
- Unknown Speckle field (coherent)
- Fast DM modulation
- Fast focal plane images
- Speckle SENSING
- Speckle NULLLING
- Calibrated image (incoherent planet light)

COHERENT DIFFERENTIAL IMAGING

Known Speckle field (coherent)
Coherent Speckle Differential Imaging
Speckle control
→ remove speckles in $\frac{1}{2}$ field dark hole
CURRENT/NEW technologies

300Hz speckle control loop (~1kHz frame rate) is optimal

Residual speckle at ~1e-6 contrast and fast → good averaging to detection limit at ~1e-8

Assumes:
- high-sensitivity WFS
- speckle control

Expected limit
Predictive control → 100x contrast gain?

Fig. 3.—Top left: 2D-tracks for true pointing (red), predicted pointing (blue) and last measured position (green). Top right: Residual pointing error. Bottom: Single axis (x) values.
Linear Dark Field Control (LDFC)

Speckle intensity in the DF are a non-linear function of wavefront errors → current wavefront control technique uses several images (each obtained with a different DM shape) and a non-linear reconstruction algorithm (for example, Electric Field Conjugation – EFC)

Speckle intensity in the BF are linearly coupled to wavefront errors → we have developed a new control scheme using BF light to freeze the wavefront and therefore prevent light from appearing inside the DF
Key technologies need rapid maturation from paper concepts to system integration

- Paper concept
- Lab demo
- On-sky operation

- High performance coronagraphy
- Diffraction-limited WFS
- Multi-lambda WFS
- Coronagraphic LOWFS
- Atmospheric speckle control
- Optimal predictive control
- Real-time WFS → PSF calibration
- Coherent differential imaging
- High spectral R template matching
- Linear Dark Field Control

SYSTEM INTEGRATION
• **Flexible** high contrast imaging platform
• Meant to **evolve to TMT instrument** and validate key technologies required for direct imaging and spectroscopy of habitable exoplanets

Core system funded by Japan
Modules/instruments funded by Japan + international partners:
- IFS funded by Japan, built by Princeton Univ
- MKID$s funded by Japan, built by UCSC
- SAPHIRA camera provided by UH
- VAMPIRES instrument funded and built by Australia
- FIRST instrument funded and built by Europe

**SCExAO is an international platform to prepare ELT imaging of habitable planets around M-type stars**
The wavefront control feeds a high Strehl PSF to various modules, from 600 nm to K band.

**Visible (600 – 950 nm):**

**VAMPIRES**, non-redundant masking, polarimetry, with spectral differential imaging capability (h-alpha, SII)

**FIRST**, non-redundant remapping interferometer, with spectroscopic analysis

**RHEA**, single mode fiber injection, high-res spectroscopy, high-spatial resolution on resolved stars

**IR (950-2400 nm):**

**HiCIAO** - high contrast image (y to K-band)

**SAPHIRA** - high-speed photon counting imager, (H-band for now)

**CHARIS** - IFS (J to K-band)

**MEC - MKIDs** detector, high-speed, energy discriminating photon counting imager (y to J-band)

**NIR single mode injection**, high throughput high resolution spectroscopy. Soon will be connected to the new IRD

**Various small IWA (1-3 I/D) coronagraphs** for high contrast imaging – PIAA, vector vortex, 8OPM

**GLINT** - NIR nulling interferometer based on photonics
Subaru Coronagraphic Extreme Adaptive Optics
Fiber-fed instruments (not visible here):
- RHEA (visible IFU, R=70,000)
- IRD (near-IR spectrograph, R=70,000)
+ experimental photonics spectro
SCExAO near-IR bench, End 2016

HiCIAO or MKIDS

CHARIS

Near-IR InGaAs cameras → to be replaced with EL technology

Near-IR nuller

SAPHIRA
Facility Adaptive Optics system

- Sharpens image

High speed pyramid wavefront sensor

- Measures aberrations
- 14,400 sensors (pix)

3.5 kHz

Extreme-AO LOOP

2000 actuator Deformable mirror

- Removes starlight

10-200 Hz

CORONAGRAPHIC LOW ORDER LOOP

Near-IR camera

- Measures low-order aberrations

800 – 2500 nm

(rejected by coronagraph)

~2 kHz

SPECKLE CONTROL LOOP

MKIDs camera

- Measures residual starlight

800 – 1350 nm

CHARIS spectrograph

- Exoplanet spectra
- Slow speckle calibration

Visible light instruments

- VAMPIRES, FIRST, RHEA

Near-IR instruments

- Nuller, HiCIAO, IRD

~0.5 Hz

2000 actuator Deformable mirror coronagraph system

- Removes starlight

10-200 Hz

CORONAGRAPHIC LOW ORDER LOOP
Measured photon efficiency (SCExAO, sub-l/D modulation pyramid)

10% photon efficiency on LO modes (2000x higher than optimal SHWFS for TT)

Efficiency drop due in part to DM influence function overlap (uncompensated in this figure)
Preliminary VAMPIRES science

Diffraction-limited imaging in visible light

750nm, 1kHz imaging log scale

Video

Summed image
Preliminary VAMPIRES science
Circumstellar dust around Red Supergiant μ Cephei

Model-fitting reveals extended, asymmetric dust shell, originating within the outer stellar atmosphere, without a visible cavity. Such low-altitude dust (likely Al$_2$O$_3$) important for unexplained extension of RSG atmospheres.

Inner radius: 9.3 ± 0.2 mas (which is roughly $R_{\text{star}}$)
Scattered-light fraction: 0.081 ± 0.002
PA of major axis: 28 ± 3.7 ° • Aspect ratio: 1.24 ± 0.03

Left: model image, shown in polarized intensity. Middle: model image show in four polarisations. Right: Model image (intensity), shown with wide field MIR image (from de Wit et al. 2008 – green box shows relative scales. Axis of extension in MIR image aligns with the close-in VAMPIRES image.
Preliminary VAMPIRES science
AB Aur star, polarimetric imaging mode

HiCIAO, near-IR

VAMPIRES (preliminary data reduction)
Current PSF stability @ SCExAO

Highly stable PSF for coronagraphy
SCExAO provides sensing and correction at 3.5 kHz
14,400 pixel WFS → 2000 actuators

1630nm (SCExAO internal camera)
3 Hz sampling
High Speed Speckle Control

Main SCExAO upgrade: High speed speckle control with MKIDs

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- Fast DM modulation
- Fast focal plane images
- Speckle SENSING
- Speckle NULLLING
- Known Speckle field (coherent)
- Unknown Speckle field (coherent)
- Unknown planet light (incoherent)
- Calibrated image (incoherent planet light)

COHERENT DIFFERENTIAL IMAGING

Subtract
speckle nulling results on-sky (June 2014)

Single frames: 50 us

Sum of 5000 frames: shift and add

Meta data:
- Date: 2\textsuperscript{nd} or June
- Target: RX Boo (also repeated on Vega)
- Seeing: <0.6”
- AO correction: 0.06” post-AO corrected in H-band (0.04” is diffraction-limit)
- Coronagraph: None (used Vortex on Vega)

Martinache. et. al.
SAPHIRA Infrared APD array

HgCdTe avalanche photodiode manufactured by Selex

Specifications
320 x 256 x 24μm
32 outputs
5 MHz/Pix

50 frame average
High speed speckle modulation

1.6 kHz frame rate, H-band
(played at 30 Hz)

Speckles modulated at 1 kHz
Electron-injector nearIR camera
(Northwestern Univ / Keck foundation)

Electron Injector

Absorption region

3 µm Electron-injection speckle imaging camera

1 µm Electron-injection low-order wavefront sensing (pointing) camera
MKIDS camera (built by UCSB for SCExAO)

Photon-counting, wavelength resolving 140x140 pixel camera

Pixels are microwave resonators at ~100mK photon hits → resonator frequency changes

Photon-counting near-IR MKIDs camera for kHz speed speckle control under construction at UCSB

Delivery to SCExAO in CY2017
SCExAO@Subaru → TMT

Demonstrate and validate performance on Subaru prior to deployment on TMT

→ Goal: be ready to go as soon as telescope ready (visitor instrument ?), with well understood instrument
  → mitigates risks, minimizes need for engineering time on TMT
  → benefits from yrs of experience on Subaru (loop control, data reduction algorithms, observing strategy)

→ Subaru provides path to quickly and safely integrate/validate new technologies prior to instrument deployment on TMT

Open international effort engaging TMT partners.
Expected overlap with development team of 2\textsuperscript{nd} generation, more capable ExAO system. Re-use experience/technologies and possibly hardware to reduce schedule/cost/risk of 2\textsuperscript{nd} generation instrument.
Notional plan toward TMT instrument

Path to TMT requires new AO woofer (~120x120 DM elements) to be built. Likely US/Japan/Canada joint effort.
Conclusions

Habitable planets can be imaged on ELTs (physics and nature are on our side)
ELTs can operate at ~1e-5/1e-6 raw contrast and photon-noise limited detection limit
→ characterization (spectroscopy) of 1e-8 habitable planets accessible around
dozens of nearby stars, mainly near-IR/visible

Ideal targets are M0-M5 stars within 5pc

BUT: conventional instrument development process is slow compared to the pace of
science in technology progress in our field
→ Schedule for (near-)first light instrument on ELT is very challenging… still lots of
work to be done
→ We are exploring, and advocating for a fast path from 8-m telescope to TMT, to
yield early science and mitigate risks for longer path 2\textsuperscript{nd}/3\textsuperscript{rd} generation instrument